

Description

Analogue amplifier with multiplexing capability

5 The invention refers to an analogue amplifier to increase circuit testability by featuring additional multiplexing capability.

10 Any procedure carried out upon an integrated circuit intended to establish its quality, performance or reliability is commonly called testing.

15 Testing can be carried out at different stages during the development of an integrated circuit; different procedures are followed, according to particular goals and circuit type, for each development stage.

20 The degree to which an integrated circuit facilitates the establishment of test criteria and the performance of tests to determine whether those criteria have been met is commonly referred as testability.

25 According to existing literature, integrated circuits testability can be quantified by means of existing capacity to control and or to observe voltages on relevant nodes in the integrated circuit. These magnitudes are commonly referred as controllability and observability.

30 The twin requirements of high precision and accuracy in signal measurement are superimposed to those basic requirements of controllability and observability to establish proper test criteria for modern high-speed communication circuits. On the other hand, new technologies make more and more defects to be non-visible, new failure

mechanisms emerge and a relevant number of circuit features are unsimulatable.

5 As a consequence, test cost and complexity increases, but also a higher risk exist to produce delays in bringing products to market or just to suffer from yield detractors that lead to higher manufacturing cost.

10 Setting up design procedures that include some constrains to increase circuit testability is a common approach to address that problem.

15 Testability can be improved either by increasing the controllability or the observability of some internal nodes. Identifying a testability issue, and therefore choosing proper nodes upon which to act in order to improve their observability or their controllability is most of the times an ad hoc issue.

20 Conventional approach to raise up internal nodes controllability or observability uses multiplexors to provide alternative signal paths. However, because of the ad-hoc nature of the task, top level floor plan layout constrains may lead to situations where it is not possible to include
25 new multiplexor blocks in the original design without severe impact upon schedule because of the re-design effort due.

30 Fig. 1 shows a not accessible node in the signal path which is driven by an analogue amplifier. To test such a not accessible node a design for test solution according to the state of the art is shown in Figure 2. For access to the node a multiplexor is provided so that a test signal can be applied directly to the node (e.g. from an external signal generator). The multiplexor is controlled by a mode control

signal which switches between a test signal T and the amplified normal signals S of the signal path. All signals are differential signals.

- 5 The drawback of a multiplexor-based solution is that the load capacitance is increased. Further providing a multiplexor increases the necessary area on the chip such increasing production costs. A further drawback is that because of the additional multiplexor the power consumption is increased.

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Accordingly it is the object of the present invention to provide means which allow a better testability by increasing internal controllability.

- 15 This object is achieved by an analogue amplifier having the features of main claim 1.

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Further advantages of the present invention are that the redesign effort is minimal, that the silicon area overhead is minimal and that the increase of the power supply current consumption is minimal.

The invention provides an analogue amplifier with multiplexing capability comprising:

- 25 an input port for receiving an analogue signal (S),
a test input port for receiving a test signal (T),
an output port for transmitting an analogue signal (O),
a control input for receiving a test control signal (CTRL-mode) switching the amplifier between a normal amplifying mode and a test mode,
30 wherein in the normal amplifying mode the analogue signal in the input port (S) is amplified to the output port (O),
wherein in the test mode the test signal (T) is routed to said output port (O).

The basic idea of the present invention is that in the main signal propagation path of analogue integrated circuits a number of amplifiers are provided to drive proper internal nodes in order and to guarantee the required signal to noise ratio. Whenever a controllability issue is detected the design of some amplifier is modified to include multiplexing capabilities that allow injecting test signals within the main signal propagation path with minimal redesign effort and minimal impact upon normal operation mode of the required amplification function.

In a preferred embodiment of the analogue amplifier according to the present invention the amplifying transistor has a first terminal switched to said signal input in the normal amplifying mode, a second terminal which is connected to an output port of that amplifier and to a load device which is switched to a first supply voltage (VDD) in said normal amplifying mode, and and a third terminal connected to a tail current sink.

In a preferred embodiment of the analogue amplifier according to the present invention the tail current sink comprises a transistor with a first terminal switched to a bias voltage in said normal amplifying mode and to a second supply voltage (V_{ss}) in said test mode.

In a preferred embodiment of the analogue amplifier according to the present invention the load device connected to the amplifying transistor is switched to the test input in said test mode.

The amplifier is in a preferred embodiment a fully differential amplifier.

5 The test signal is generated in a first embodiment by a built in test pattern generator.

The test signal is applied in an alternative embodiment via a pad from an external test pattern generator.

10 In the following preferred embodiments of the analogue amplifier according to the present invention are described with reference to the enclosed figures.

15 Figure 1 shows the signal path in an analogue circuit according to the state of the art;

Figure 2 shows a conventional approach to increase the controllability of an internal node non accessible from any primary input/output of the circuit under test.
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Figure 3 shows a pll circuit with added multiplexor according to the state of the art to increase controllability by bypassing the amplified VCO output.

25 Figure 4 shows a fully differential amplifier, tail current and bias generation according to the state of the art;

Figure 5 shows an arrangement comprising an amplifier according to the present invention in order to increase the
30 controllability of the circuit node driven by said amplifier;

Figure 6 shows a preferred embodiment of the analogue amplifier according to the present invention;

Figure 7b shows a differential output voltage from an amplifier according to the state of the art as shown in figure 4 and figure 7a shows a differential output voltage from an ADfT-analogue amplifier according to the present invention as shown in figure 6;

Figure 8 shows the spectral content of the output voltages of a conventional amplifier and of the analogue amplifier according to the present invention;

Figure 9 shows noise figure curves of a conventional amplifier and of the analogue amplifier according to the present invention;

Figure 10 shows the 1 dB compression point of the conventional amplifier according to the state of the art;

Figure 11 shows the 1 dB compression point of the analogue amplifier according to the present invention;

Figure 12 shows the IP3 (3rd order intersection point) for the conventional amplifier;

Figure 13 shows the IP3 for the amplifier according to the present invention.

Figure 3 shows a conventional approach for testing a phase locked loop, (PLL), circuit within mixed signal circuits. A phase locked loop is a system with induced feedback to maintain an output signal in a specific phase relationship with a reference signal. The pll-circuit shown in figure 3 comprises of phase frequency detector PFD controlling a charge pump CP which supplies a deviation signal to the low pass filter LP. The filtered signal is supplied to a voltage

controlled oscillator VCO. The voltage controlled oscillator VCO is a circuit that produces an AC-output signal whose frequency is proportional to the input control voltage. The VCO output signal is amplified by a conventional amplifier as shown in figure 4. For test purposes a multiplexor is provided at the output of the amplifier in the conventional approach as shown in figure 3. In the feedback loop a division circuit is provided which produces an output signal whose frequency is an integer division of the input signal frequency. The VCO signal is fed back within the pLL-circuit through a high speed $1/N$ frequency divider. The proper operation of these frequency divider is essential to guarantee a good pLL-performance.

By providing a multiplexor to the output of amplifier A the load capacitance, the area overhead and the power supply consumption are increased.

Figure 4 shows a conventional state of the art differential amplifier A. The amplifier A is connected to a biasing circuit. The conventional amplifier A as shown in figure 4 comprises two input terminals and two output terminals. The input terminals are connected to the gate terminals of amplifying MOS-transistors T_a . The source nodes of the amplifying transistors T_a are connected at a common node to a tail current sink implemented by transistor T_b having a gate which is biased by a reference voltage. The drain terminals of the amplifying transistors T_a are connected via resistors to a positive supply voltage VDD.

According to the present invention the design of the conventional amplifier A as drawn in figure 4 is modified to increase the controllability of an internal node driven by

said amplifier. Thus the testability of the circuit under test including said amplifier is increased too.

Figure 5 shows a block diagram of an analogue amplifier 1 according to the present invention. The analogue amplifier 1 according to the present invention as shown in figure 5 can be switched via a control mode signal between a first normal amplifying mode and a second test mode. A control mode signal is used to switch between both modes. The signal generator can be located externally or be built in.

The function of the amplifier 1 in the normal mode can be described as:

$$Z(S,T) = K_1 \times S + K_2 \times T$$

wherein S is the signal of the signal path,
T is the test signal and
 K_1, K_2 are constants.

Since the function of the conventional amplifier to be modified can be described as:

$$Z(S) = K_1 \times S$$

the first constant K_1 of the modified amplifier according to the invention is as close as possible to the original amplifying constant K_1 of the conventional amplifier.

In the normal test mode the constant K_2 of the analogue amplifier 1 according to the present invention is as small as possible ($K_2 \rightarrow 0$).

When the analogue amplifier 1 according to the present invention is switched to the test mode its operation can be described as:

5 $Z(S,T)=K_3 \times S + K_4 \times T$

In an ideal implementation of the differential amplifier 1 according to the present invention, the constant K_3 is zero to isolate the signal S of the signal path from the injected
10 test signal T . The constant K_4 is close to or lower than one in an ideal implementation ($K_3 = 0$; $K_4 \leq 1$).

Figure 6 shows a circuit diagram of a preferred embodiment of a differential analogue amplifier 1 according to the present
15 invention. The analogue amplifier 1 is fully differential.

The differential analogue amplifier 1 comprises an input port 2-1, 2-2 for receiving an analogue signal S . The amplifier 1 further comprises a test input port 3-1, 3-2 for receiving a
20 test signal T . Further a control input port 4 is provided for receiving a test control signal switching the amplifier 1 between a normal amplifying mode and a test mode. In the normal amplifying mode the amplifier 1 as shown in figure 6 amplifies the analogue signal S and transmits the amplified
25 signal via an output port 5-1, 5-2 to an internal node within the integrated circuit. In the test mode the test signal T is transmitted to that internal node.

The amplifier 1 comprises an amplifying transistor 6-1, 6-2
30 having a gate terminal 7-1, 7-2, a source terminal 8-1, 8-2 and a drain terminal 9-1, 9-2. The gate terminals 7-1, 7-2 of the amplifying transistors 6-1, 6-2 are connected via lines 10-1, 10-2 and first switches 11-1, 11-2 to the signal input terminals 2-1, 2-2.

The drain terminals 9-1, 9-2 of the amplifying transistors 6-1, 6-2 are connected via lines 13-1, 13-2 to the output port 5-1, 5-2 of the amplifier 1. Connected to lines 13-1, 13-2 are resistors 14-1, 14-2. The source terminals 8-1, 8-2 of the amplifying transistors 6-1, 6-2 are connected via a line 15 to a drain terminal 16 of a tail current sink comprising a transistor 17 having a source terminal 18 connected to a second negative supply voltage V_{ss} . The current tail transistor 17 comprises a gate 20 connected via a line 21 and via a second switch 22 to a biasing reference voltage supplied to a terminal 23 of the amplifier 1. Line 21 further connects gate 20 of current tail transistor 17 to a drain terminal of a switching transistor 24. The gate 20 of the tail current transistor 17 can be switched by the third switch 24 to the negative supply voltage V_{ss} .

The load devices 14-1, 14-2 connected to the amplifying transistor 6-1, 6-2 are connected via lines 26-1, 26-2 and fourth switches 27-1, 27-2 to a positive supply voltage. The load devices 14-1, 14-2 are further connected via fifth switches 28-1, 28-2 to the test signal input port.

All switches 11-1, 11-2, 22, 24, 27-1, 27-2, 28-1, 28-2 of the amplifier 1 are controlled by a test control mode signal applied to the amplifier by terminal 4. Two inverter circuits 29-1, 29-2 invert the test control mode signal, wherein the inverter circuit 29-1 supplies the signal not (T-CTRL) to switches 28-1, 28-2, and to switch 22, and wherein inverter circuit 29-2 supplies the signal T-CTRL to switches 11-1, 11-2, switch 24 and switches 27-1 and 27-2.

The following table shows the states of the switches within the amplifier 1 drawn in figure 6 according to the present invention.

switch	test mode	normal mode
S_{28-1}, S_{28-2}	On	Off
S_{27-1}, S_{27-2}	Off	On
S_{11-1}, S_{11-2}	Off	On
S_{22}	Off	On
S_{24}	On	off

In the normal amplifying mode switch 24 and switch 28-1, 28-2 are switched off and switches 27-1, 27-2, 11-1, 11-2, 22 are switched on. By means of the switch 28-1, 28-2 the test signal is cut off from the output terminal 5 of the amplifier 1. The gate 7-1, 7-2 of the amplifying transistor 6-1, 6-2 receives the analogue signal via a switch 11-1, 11-2 and transmits the amplified signals to output port 5-1, 5-2 of the amplifier 1. In the normal amplifying mode the gate 20 of the tail current transistor 17 receives the biasing reference voltage via closed switch 22. Since switch 27 is also closed in the normal amplifying mode the amplifying transistor 6 receives the positive supply voltage V_{DD} via the loading resistors 14-1, 14-2.

When switched to the test mode switches 28-1 and 28-2, and switch 24 are closed. At the same time switches 27-1, 27-2, 11-1, 11-2 and 22 are opened. While switching off switch 27 the amplifying transistor 6 is disconnected from the positive supply voltage V_{DD} and cut off. By opening switch 11-1, 11-2 no input signal is supplied to the gate 7-1, 7-2 of the amplifying transistor 6-1, 6-2. By isolating gates of the amplifying transistors 6-1, 6-2 from the input signal via switches 11-1, 11-2 the signal S is isolated from the output port 5-1, 5-2.. This ensures that the test signal T supplied to the output port 5-1, 5-2 via the load resistors 14-1, 14-2

is not affected by spurious signals coming from the input terminals 2-1, 2-2.

By switching off switch 22 the transistor 17 does not get a
5 biasing reference voltage. Furthermore its gate 20 is
switched to the negative supply voltage V_{SS} by closing switch
24. In this manner the transistor 17 is cut off completely
and the tail current going to ground is nullified. The
10 amplifier design as shown in figure 6 focus on the tail
current sink and loads of the amplifier 1 which are modified
by the switches to reconfigure the operation of the
amplifier. The design of a conventional amplifier is modified
by adding switches that disconnect the amplifying transistor
15 from the incoming signal and the tail current sink transistor
from the bias circuitry. The design is modified in such a way
that the injection of the test signal T in the signal path
has a minimal impact upon the circuit normal operation.

20 Figures 7-12 come from simulation analysis carried out at the
operational frequency of 1.6 GHz.

Figure 7a, 7b show the differential output wave forms of an
original differential amplifier as shown in figure 4 in
comparison to the differential output of the amplifier 1
25 according to the present invention as shown in figure 6. The
input signal used is a monotonic sinusoidal at 1,562 GHz.

Figure 8 shows the spectral content of the output voltages of
the conventional amplifier (a) shown in figure 4 and the
30 amplifier (b) according to the present invention as shown in
figure 6.

The increase of the noise figure at the operation frequency
is due mainly to the drop in conversion gain related to the

attenuation effect of transistors 11-1 and 11-2. The second largest contribution to the relative increase in the noise figure at the operation frequency is coming from transistor switches 27-1, 27-2 accounting to less than a quarter of the contribution of transistor switches 11-1, 11-2.

Figure 9 shows the plot of noise figures with a measurement mark at a operating frequency (conventional amplifier a; amplifier according to the present invention b).

Figures 10 to 13 show different plots of measuring inter-modulation distortion products. The performance of the amplifier according to the present invention it is about 1,5 to 2 dBm better than the original amplifier according to the state of the art.

Parasitic capacitance to ground together with the on resistance in transistors 11-1, 11-2 implement a low pass filter at the inputs 2-1, 2-2 of the differential amplifier in the modified circuit. The attenuation provided by this filter at the operating frequency which accounts for the gain drop depicted in figure 7 is also responsible for the improvement observed in the circuit linearity. Since the filter attenuation reduces the input power to the differential amplifier it behaves better in terms of intermodulation distortion.

Area overhead due to the amplifier design according to the invention accounts for about 9% of the original area due to the original amplifier design. This figure expressed in terms of a total pLL-area, where the amplifier is located, represents about only 0.023% since the amplifier itself takes only about 0.25% of the total pLL-area. In the test mode a low impedance propagation path exist between the test port 3-

1, 3-2 and the corresponding circuit output nodes 5-1, 5-2, respectively.

Transistors 28-1, 28-2 used to disconnect the test ports 3-1, 3-2 are dimensioned according to the impedance requirements. These elements are placed in series with the loading resistors.

According to the present invention a device under test can be reconfigured and its outputs multiplexed to inject test signals. Consequently it is possible to increase the controllability of relevant nodes of the circuit under test, and therefore its testability is also enhanced.

The present invention can be adapted to different operating frequencies, ranging from DC to frequencies in the order of tens of GHz typically used in optical communication circuits. The present invention is applicable to any analogue circuit whose controllability is to be increased.

The modification of the design of a conventional amplifier makes possible to inject a test signal (T) with a minimum impact upon the circuit performances. Further the area overhead due to the circuit modification remains below 10% of that of the differential amplifier.